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Title:

Lithic miniaturization as adaptive strategy: A case study from Boomplaas Cave, South Africa

1 Introduction

Late Pleistocene (c. 125–12 ka) humans evolved in contexts of climatic volatility, episodic intense cooling and landscape reorganization as the globe cycled through relatively warm and cool interglacial-glacial climatic shifts, seas rose and fell, and ancient coastlines advanced and retreated (Marean 2016). These broad climate patterns had dramatic and variable effects on local climate and vegetation with consequences for key resources (plants, animals, and water) upon which foraging societies depended. Patterning in climate and environment that influences resource availability is a key influence on human behavioral variability (Binford 2001; Kelly 2013). Shifts in these biogeographic dynamics precipitated significant demographic, genomic, and technological adjustments in foraging societies (Henn et al. 2011; Mackay et al. 2014; Soares et al. 2016).

Archaeological data show that Late Pleistocene *Homo sapiens* pioneered efforts to rapidly generate novel solutions for survival in diverse, alien and often challenging environments, exhibiting adaptive plasticity (e.g. Barker et al. 2007; d'Errico and Stringer 2011). Among such systems are miniaturized lithic technologies, including small cores and flakes, blades (bladelets), small backed and retouched tools, which provide several benefits such as raw material economy, functional flexibility, and replaceability (e.g. Elston & Kuhn 2002; Pargeter & Shea 2019). These economic benefits would have direct payoffs in environments where suitable raw material was scarce, where knappable rock occurred in small package sizes, or where groups had to maintain high levels of mobility/technological readiness (Kuhn 1995). Archeologists increasingly observe highly variable patterns of lithic miniaturization through time and across space (Lewis 2017), suggesting that it was not an inevitable consequence of human tool use, but more likely a strategic behavior deployed in specific environments and periods.

1.1 Explaining changes in miniaturized lithic systems

Archaeologists propose several models to explain lithic miniaturization including those that emphasize small tools' symbolic, functional, and economic advantages (Elston and Kuhn 2002). Models that are currently most amenable to testing emphasize some aspects of lithic miniaturization's adaptive benefits, including its relationship to mobility strategies seen through site occupation intensification patterns and seasonal scheduling (Hiscock et al. 2011). Archaeologists have argued site occupation variability played a significant role in hunter-gatherer technological choices in general (e.g. Binford 1990; Kelly 1983) and lithic miniaturization in particular (e.g. Kuhn 1994; Nelson 1991). Tryon and Faith (2016), for example, argue increasing site occupation intensity at Nasera rockshelter in Tanzania ~40ka through processes connected with wider population pressure resulted in decreased access to raw materials and increased reliance on local rocks. These demographic processes placed greater pressure on humans to conserve raw material by using increasingly miniaturized lithic reduction strategies (cf. Shott 1989). Their model links increased site occupation intensity with resource scarcity and greater lithic miniaturization (small core reduction). It also finds that more efficient technologies (i.e. bipolar reduction related to bladelet production) manifest at times of increased site occupation intensity (cf. Eren et al. 2013).

Several archaeologists have invoked paleoenvironmental change and seasonal scheduling of resource exploitation to explain lithic miniaturization's variability (e.g. Elston and Kuhn 2002; Hiscock 1994; Lombard and Parsons 2008; Petraglia et al. 2009; Clarkson et al. 2018a). The argument follows that more mobile populations' exploitation of generally sparse, patchy, or seasonally variable resources would have increased selective pressure for smaller, lighter, more reliable and multi-functional miniaturized toolkits. Miniaturized technological strategies suitable for use on a wider range of rock types and small clast sizes would have further enhanced this strategy's flexibility and utility.

Mitchell (1988) argues that the shift towards miniaturized lithic strategies was a response to 'time-stress' in ecologically challenging or seasonally distinct environments (cf. Torrence 1983). He argues that reduced ecological productivity resulted in increased pressures on hunter-gatherers to divide time between finding food, making and maintaining technology, avoiding predators, finding mates, and investing in offspring (Hames 1992). These time costs would increase in contexts where raw material sources are protected, are unpredictable, are of poor quality, where rocks are small, occur in shapes on which reduction is difficult, or a combination of factors (Hayden 1989). One strategy to manage these time costs is to adopt miniaturized technological strategies that maximize flake yield per unit of raw material, that can be used on a range of raw material package sizes, and that reduce the frequency and magnitude of raw material procurement (Mackay and Marwick 2011). Archaeologists argue that small elongated flakes, or bladelets, provide more potential utility per number of artifacts transported and maximize the use of small cores (e.g. Bar-Yosef & Kuhn, 1999; Mackay, 2008; Muller & Clarkson, 2016). These observations suggest that when there was strong directional selective pressure encouraging lithic miniaturization, the proportion of the relatively small stone tool evidence referable to bladelet production should increase relative to evidence referable to smaller flake production (Pargeter & Shea, 2019).

1.2 Hypotheses and predictions

This paper tests two hypotheses to account for the use of lithic miniaturization as an adaptive strategy. The first concerns site occupation intensity- a variable linked to group mobility, population density, and technological organization (Dibble and Rolland 1992). Following Tryon and Faith's (2016) observations at Nasera rockshelter, we expect evidence for increased flaking efficiency (i.e. bipolar reduction and bladelet production) and an uptick in lithic miniaturization (increased core reduction intensity) in periods of increased site occupation intensity. Such a finding would imply that the structure of lithic miniaturization was an adaptive response resulting in part from broader demographic processes and their effects on access to resources.

The seasonal structure of resources is another key environmental predictor of hunter-gatherer mobility strategies and technological organization (Binford 1982, 2001). Periods of resource abundance become shorter and more sharply defined in more seasonal environments resulting in greater energy expenditure to locate and procure resources (Bousman 1993; Harpending and Davis 1977). Drawing from a worldwide ethnographic dataset, Kelly (1983) confirmed that seasonality was a significant predictor of the number and distance of annual hunter-gatherer moves, especially for groups dependent on large mammal hunting. Factors that affect mobility strategies and foraging behavior will ultimately have consequences for hunter-gatherer technological strategies (Barton and Riel-Salvatore 2014; Kuhn 1995; Mackay et al. 2014; Parry and Kelly 1987; Riel-Salvatore and Barton 2004; Wilkins et al. 2017). Extended periods of residential stability in less seasonal environments can stress sources of good quality lithic raw material resulting in more intensive reduction strategies corresponding with more intensively reduced cores and flakes (Dibble 1995). If seasonality does ultimately affect hunter-gatherer mobility and technological organization, then one would expect to see increased flaking intensification in contexts of reduced seasonality.

1.3 Background to Boomplaas Cave

South Africa's southern Cape landscape is one of a handful regions in Africa with rich inland archaeological deposits covering both the LGM and Late Glacial. Ongoing research in the region has built a rich body of paleoenvironmental evidence (e.g. Bar-Matthews et al. 2010; Braun et al. 2018; Carr et al. 2016; Chase et al. 2018, 2019; Chase and Meadows 2007; Engelbrecht et al. 2019; Talma and Vogel 1992) and abundant well-dated archaeological sequences (e.g. H. J. Deacon and Brooker 1976; Henshilwood 2005; Jacobs et al. 2008; Mackay 2016a; Marean et al. 2010). Together these data provide a rich framework for exploring patterns in the organization of human mobility and environment interactions that is unique in African paleoanthropological research.

Boomplaas is the southern Cape's richest inland archaeological cave site. The site is a limestone cave with a 225 m^2 floor area in South Africa's Western Cape Province about 80 km inland from the current Indian Ocean coastline (H. J. Deacon 1979) (**Figure 1**). Overlooking the Cango Valley along the flanks of the Swartberg Mountain Range, the site sits between the modern Montane Fynbos/Karoo Biomes at 700 m above sea level (**Figure 1**). The Swartberg is the Cape Fold Belt's innermost range bordered on the north by the Great Karoo and the south by the Klein Karoo, both of which are arid to semi-arid regions. The region around Boomplaas receives on average 326 mm of annual rainfall across the summer and winter months. The mean annual evapotranspiration (MAE), accounting for the combined process of both evaporation from soil and plant surfaces and transpiration through plant canopies (Irmak and Haman 2003), relative to annual rainfall (MAP / MAE = 0.24; data from Trabucco and Zomer 2009) indicates a semi-arid environment. High evapotranspiration rates and ~80% of the grasses being C_4 make the Cango Valley especially sensitive to climate change and amplified aridity. Despite the general aridity in surrounding areas, the Grobbelaars River drains the Cango Valley and provides permanent freshwater sources.

Excavated by the late Hilary Deacon between 1974 and 1979, Boomplaas Cave preserves a long occupational sequence extending from c. 60 ka and probably earlier at its base (H. J. Deacon 1979). Deacon's excavations initially uncovered a 20 m^2 area, but he narrowed them to 7 m^2 at a depth of 2 m which he excavated to bedrock (H. J. Deacon 1995). Occupation deposits are variably comprised of thin discrete hearths, humic and ash features combined into members approximately 0.05 to 0.2 m thick. All excavated materials were dry-sieved through 3 mm mesh except for areas with high microfauna frequencies, which were sieved through 2 mm mesh.

The current study focuses on Boomplaas' LGM and Late Glacial deposits dated ~26 – 11 kcal BP. Several lines of evidence including charcoal, faunal analyses, stable isotopes, and sediment studies show that Boomplaas' major occupation pulses occurred alongside large-scale LGM and Late Glacial environmental changes with decreased local environmental productivity and increased aridity after the LGM (Chase et al. 2018; H. J. Deacon and Lancaster 1988; H. J. Deacon et al. 1983; Faith 2011, 2013a,b; Faith et al. 2019; Sealy et al. 2016; Talma and Vogel 1992; Webley 1978). Humans appear to have chosen the Cango Valley for short-lived, sometimes intensive and repeated habitation in the LGM with the nearest coastline an estimated 180 km away (Fisher et al. 2010). Marine shell first appears in the Boomplaas sequence during the Late Glacial at c. 16 kcal. BP, which corroborates increased contact with coastal contexts at a time of rapid sea level rise along the Paleo-

Agulhas plain, either through exchange or group movement (J. Deacon 1984). Together, these factors hint at complex processes of social change in the Cango Valley region in the face of habitat shifts and landscape reorganization across the southern Cape driven in part by rising sea levels. Faith (2013a) argues that the combination of growing population density, coupled with the attendant increase in competition for resources, may have underpinned the expansion of human populations into less favorable inland habitats, including the Cango Valley (cf. Inskeep 1978).

1.4 Previous efforts to test the relationship between lithic technology and paleoenvironmental changes at Boomplaas Cave

J. Deacon (1984) was the first to test the hypothesis that lithic technological change at Boomplaas Cave was stimulated by environmental change. Her work drew on a set of lithic techno-typological categories generated from over 225,000 lithics at Boomplaas Cave, Nelson Bay Cave, and Kangkara (Fig. 1) combined with paleoenvironmental data from stalagmites, charcoal, micro- and macromammals. J. Deacon's results showed no consistent relationship between changes in the stone tool typology and environmental change. Chase and colleagues (2018) recently revisited the issue of climate change and lithic technology at Boomplaas, drawing on J. Deacon's (1984) lithic data. They combined observations from the Boomplaas faunas with $\delta^{13}C$ and $\delta^{15}N$ stable isotopic data from nearby (~70km west of Boomplaas) Seweweekspoort to test J. Deacon's hypothesis that climate change did not affect technological change in the Cango Valley and surrounding areas. Chase and colleagues found strong coupling of environmental, subsistence and technological shifts, but no evidence to directly link specific lithic tool types (blades) with diminished subsistence conditions. Differences between J. Deacon (1984) and Chase and colleagues (2018) arise largely from differences in analytical techniques, theoretical orientations, and newly generated dates and paleoenvironmental data. Chase and colleagues situate their study within a behavioral ecological framework and derive lithic variables relevant to addressing questions of hunter-gatherer technological organization and scheduling (sensu Nelson 1991; Shott 1986).

We aim to refine our understanding of hunter-gatherer technological organization at Boomplaas Cave by overcoming several limitations of the Chase et al. (2018) study that stem from constraints in their lithic dataset. First, given the data at hand (J. Deacon 1984), they focused on the relative frequencies of one miniaturized tool type (bladelets) but not on the strategies used to make these bladelets. Bladelets can be produced using a range of strategies with different costs and benefits (Pargeter and Eren 2017; Pargeter and de la Peña 2017; Pargeter et al. 2019), the least costly of which in terms of time and energy are those involving bipolar (hammer and anvil) reduction. These observations suggest that when there was strong directional selective pressure encouraging low cost lithic miniaturization and bladelet production, the proportion of the relatively small stone tool evidence referable to bipolar percussion should increase relative to evidence referable to other reduction strategies. Second, they were also uanble to include a measure of reduction intensity, which Mackay and Marwick (2011) argue is important for connecting changes in technological time costs and provisioning strategies. Third, Chase et al.'s (2018) analysis included data from only the youngest (GWA) of Boomplaas' three LGM members, as their emphasis was on those members that chronologically overlap with the Seweweekspoort hyrax middens. Analysis of the site's earlier LGM members (LPC and LP) is necessary to gain a complete perspective on LGM technological variability.

This study draws on a newly generated lithic dataset (Pargeter 2017) to address the issues raised above. The dataset describes in greater detail the technological structure of the LGM and Late Glacial lithic assemblages at Boomplaas Cave, providing a more complete picture of LGM and Late Glacial technological variability. It also draws on recent experimental data (Pargeter and de la Peña 2017; Pargeter and Eren 2017; Pargeter et al. 2019) to move beyond typological patterning in the lithic assemblage and to examine variables relevant to the technological time costs associated with different lithic miniaturization strategies. With these data we are able to address the question of whether shifts in lithic reduction are correlated with shifts in site occupation patterns and paleoenvironmental conditions and specifically the degree to which variation in the structure and organization of lithic miniaturization strategies can be considered adaptive strategies.

2 Materials and methods

The following sections provide detail on the study's main lithic, occupation intensity, and paleoenvironmental datasets. In the interests of promoting open science initiatives and computational reproducibility in archaeology (e.g., Marwick 2017), the paper's raw data and statistical code are available through the Open Science Framework (osf.io/pr65w).

2.1 Lithic analysis

The lithic analyses reported here aimed to clarify the technological variability across Boomplaas' LGM and Late Glacial occupations. Our sampling focused on two 1m^2 excavation areas P14/P15. These squares contain representative samples from each of the site's major stratigraphic members and sub-units including LGM members LP, LPC, and GWA as well as Late Glacial member CL (**see Table 1**). A sample size of at least 300 flakes/layer was selected (in layers with fewer than 300 lithics/layer, all were measured) without size cut-offs. All cores were analyzed because cores contain greater technological information than flakes. All the assemblages from the levels examined here were made predominantly (>80 %), if not exclusively, on locally abundant quartz (both hydrothermal vein quartz and crystal quartz). To control for the effects of raw material variability, our analysis focuses solely on Boomplaas' quartz assemblage.

2.1.1 Lithic attributes

The study used a standardized attribute-based framework from which we have selected variables to track changes in reduction strategies and reduction intensity. The variables also help clarify two important aspects of lithic technology – the organization of technology and the strategic use of raw materials.

We derived three summary lithic variables from these data that describe aspects of the structure and organization of lithic miniaturization at Boomplaas Cave (**see Table 2**). The variables include bipolar core frequencies, bladelet core frequencies, and an assemblage reduction intensity index (ARI) calculated as the ratio between the average flake length and average core length in each layer (Olszewski et al., 2011) (**see Table 2** for definitions of each variable). Bipolar core frequencies and bladelet core frequencies track technological differences between assemblages. Following Low & Pargeter (2020), bladelet cores must preserve evidence for the removal of at least one bladedelet in the form of a flake scar with parallel scar ridges, a flake scar length at least twice as long as it is wide, and a width < 12mm. The ARI is used to gauge the intensity of raw material use and reduction. Cores from which only few flakes have been struck should be larger (on average) than the flakes indicating a low reduction intensity (ARI <1). On the other hand, cores that have been heavily reduced on site will be smaller than the initial flakes (ARI >1) and, if reduction proceeded on site and was intensive enough, even smaller than the average size of flakes/blades. The ARI is probably a sensitive measure of mobility patterns given the expectation that archaeologists predict mobility distance and site occupation intensity affects core reduction intensity (Barton & Riel-Salvatore, 2014). These data provide a broad referential framework against which to assess patterning in our paleoenvironmental data and to test the hypothesized relationships between technological organization, site occupation intensity, and paleoenvironmental variability.

2.2 Site occupation intensity

While Boomplaas Cave was excavated with tight stratigraphic control and to an exceptionally high standard, limitations in the then current methods precluded the use micro-stratigraphic techniques or micromorphological analyses. As a result, we rely on broader descriptions of deposit accumulation, subsistence practices, and artefact discard trends to interpret site occupation patterns (**see Table 3**).

We track site occupation intensity using taphonomic signals on the large mammalian fauna. This taphonomic measure is derived from the proportion of bone surface modifications on long-bone midshaft fragments that can be attributed to human activity (cut-marks and percussion marks) relative to modifications related to non-human bone accumulators (carnivore tooth-marks and gastric etching). This provides a coarse proxy for the human versus non-human (e.g., carnivores and large raptors) contribution to the accumulation of the bone assemblage (Thompson et al. 2017a), which we interpret in terms of human occupation intensity. For example, a low frequency of anthropogenic bone modifications (equated with a high frequency of non-human modifications) implies ephemeral occupation of the cave by hunter-gatherers, allowing other taphonomic agents to introduce bone into the assemblage. Conversely, a dominance of anthropogenic bone modifications (equated with increased human modifications) implies intensive human occupation with fewer opportunities for carnivores or raptors to accumulate faunal remains in the cave.

2.3 Seasonality data

To test for the influence of seasonality on technological organization, we focus on recent data for Boomplaas' micromammal assemblages. Though there are other sources of paleoenvironmental information available from Boomplaas Cave (e.g., large mammals, charcoal), we focus on the micromammals because they represent an environmental archive that accumulated independent of human behavior.

The Boomplaas sequence contains a rich microfauna assemblage thought to have been accumulated by barn owls (*Tyto alba*) (Avery 1982). Barn owls prey on a range of micromammalian species within a small radius (c. 2-3 km) of their roost (Andrews 1990). This small foraging radius (e.g., compared to human foragers) implies that micromammals provide a localized representation of the micromammal community and the environments in which they are found.

We use the index of rainfall seasonality (summer versus winter rainfall) provided by Faith and colleagues' (2019) analysis of the Boomplaas microfauna. Their index is derived from analysis of 100+ modern barn owl-accumulated micromammal assemblages from across southern Africa. They employed canonical correspondence analysis (CCA) to establish relationships between modern species composition and estimates of rainfall seasonality provided by the WorldClim global climate database (Hijmans et al. 2005). These relationships were then used to interpret CCA ordination scores for the Boomplaas fossil micromammal assemblages in terms of precipitation seasonality (cf. Thackeray and Fitchett 2016). In the southern Cape, variations in microfauna seasonality largely track the changing influence of summer rains and their effect on the severity of the dry season (cf. Chase et al. 2015). Greater seasonality in this region reflects increased contributions from warmer season rains. Faith and colleagues' data show that the LGM at Boomplaas is characterised by a high proportion of winter rainfall, with seasonality index values matching those from modern and fossil sites at the core of South Africa's modern winter rainfall zone (Faith et al. 2019). The following Late Glacial shows a shift towards overall less seasonality—related to increased summer rainfall coupled with reduced winter rainfall (i.e., a more equable distribution of rainfall).

3 Results

Table 3 presents summaries for the three lithic variables at Boomplaas.
Reduction intensity values remain relatively low for much of the LGM with values increasing more dramatically during the Late Glacial. All of member CL's sub-units show high average reduction intensity values around 1.4 (95% CI's: 1.9-0.8) while LGM members GWA and LP show the lowest average reduction intensity values ranging between 0.7 and 0.8 (95% CI's: 0.9-0.4). Overall, patterning in these lithic variables show heightened reduction intensity in Boomplaas' Late Glacial assemblages.

Bipolar core frequencies in the CL sub-members show consistently frequencies (range: 96 % - 100 %) (see Figures 2 & 3). The LGM members show much lower bipolar core frequencies ranging from 45 % in member LPC to 81 % in member LP. Bladelet core frequencies track the bipolar core patterns with higher overall frequencies in the Late Glacial members and lower values during the LGM. Member LPC shows the greatest deviation within the LGM members with a relatively low bladelet core frequency of 12 % [95% CI: 5-22]). Together these data show that toolmakers likely used bipolar cores to make small elongated flakes more so during the Late Glacial than during the LGM. Table 3 presents summary data on the anthropogenic input index (bone surface modification frequencies). These values are low during the LGM in members LP, LPC, and GWA (range: 25 % - 30 %) with marked increased across the Late Glacial member CL (range: 87 % - 94 %). The results provide strong evidence for a shift towards greater site occupation intensity during the Late Glacial.

Figure 4 compares patterns across our suite of lithic, macrofauna, and microfauna variables. The data show clear and tightly correlated changes across all of these variables. Boomplaas' anthropogenic fauna markers track closely with the microfauna seasonality index demonstrating that the site underwent more intensive use as rainfall shifted to the warmer months, reducing its overall seasonal variability. The three lithic patterns paralell closely the trends in microfauna seasonality and site occupation intensity. Reduction intensity, bladelet and bipolar technology increased at times of increased site occupation intensity and decreased rainfall seasonality. These results support both our hypotheses and show that at Boomplaas, lithic technological organization is associated both with site occupation intensity and rainfall seasonality.

4 Discussion

Boomplaas Cave's archaeological record contributes to an increasingly coherent picture concerning Late Pleistocene human environment interactions in the southern Cape. Here we draw on several lines of evidence including lithic technology, taphonomic data on macrofauna, and micromammalian evidence to test the hypotheses that differences in lithic technological organization across the LGM to Late Glacial reflect changes in the site's occupation intensity and the local region's rainfall seasonality. Our data support both of our test hypotheses showing that lithic miniaturization strategies are linked to site occupation intensification patterns and seasonal scheduling. In particular, we find that decreasing seasonality is associated with greater occupation intensity, coupled with dramatically increased core reduction intensity, bladelet and bipolar core frequencies.

Several paleoenvironmental proxies including stable isotopes, macrofaunal specifies composition, hyrax midden data, and micromammalian data point to a major reorganization in precipitation seasonality and ecology in the southern Cape across the LGM to Late Glacial transition (Avery 1982; Chase et al. 2018; Faith 2013a; Faith et al. 2019; Klein 1978; Sealy et al. 2016; Talma and Vogel 1992; Thackeray and Fitchett 2016). These shifts would have impacted hunter-gatherer technology, mobility, and foraging strategies. Chase and colleagues (2018) draw on optimal foraging theory to examine zooarchaeological measures of foraging efficiency in Boomplaas' Late Glacial member CL. They show a strong and positive trend towards increased relative abundance of small-bodied and presumably low-ranked prey (i.e. tortoises) and the mean food utility index of large mammal skeletal elements (Metcalfe and Jones 1988) across sub-members CL 3 – 1. This decline in foraging efficiency tracks our data on increased reduction intensity across the same interval. The pattern of increased technological efficiency coupled with degraded subsistence base matches with expectations of optimal foraging theory (e.g. Broughton 1994) and with theoretical work linking ecological changes and hunter-gatherer technological organization (Harpending and Davis 1977; Kelly 1983; Mishra et al. 2013; Clarkson et al. 2018b).

Previous research has considered ecological parameters, mobility, and population demography as competing hypotheses to explain changes in technological organization (e.g., Collard et al. 2013; Thompson et al. 2017b). While considering each of these factors separately is more straightfoward, it is more realistic to view them as interelated phenomena. For example, group size, is determined by availability and distribution of resources, and equally the size and structure of a group can affect how resources are acquired and technologies are transmitted. Marean (2014) argues that the consistent use of marine resources should result in reduced mobility, larger group size, population packing, smaller territories, complex technologies, increased economic and social differentiation, and more intense and wide ranging gifting and exchange. Drawing on data from the Indian subcontinent, Petraglia and colleagues (2009) maintain that decreased ecological productivity at the onset of the LGM led to population reorganization (recorded in mtDNA haplogroups) and increased emphasis on miniaturized technological systems. Mackay and colleagues (2014) hypothesize that population coalescence and fragmentation events between ~130 – 12 ka in southern Africa and related shifts in subsistence and technology were driven largely by underlying environmental conditions. We find similar evidence suggetsing that demographic processes impacted choices of technology within a rapidly shifting biogeographical context.

The Late Glacial period in the southern Cape was marked by dynamic social and environmental changes, reduced bio-productivity, as the broader region shifted away from a productive C_3 grassland habitat to a more fragmented mixed C_3/C_4 environment (Faith 2011;

Chase et al. 2017, 2018). This was also a period of large-scale landscape reorganization as post-glacial sea-level rise caused the coastline to advance up to 120 km inland (Fisher et al. 2010). Marean and colleagues (2014) argue that the primary driver of Pleistocene change in the southern Cape was the expansion and contraction of the Paleo-Agulhas Plain, which resulted in changes in the size and structure of resources in an area that once supported productive grassland ecosystems. These processes displaced grazing species and the hunter-gatherer groups who organized their land-use strategies around their movements. Faith (2013) proposes that increased population densities stemming from the post-LGM marine transgression fueled competition for resources and may have provided the impetus to expand into less productive (non-coastal) habitats, potentially accounting for evidence for more intensive Late Glacial occupation at Boomplaas Cave. The earliest appearance of marine shell at Boomplaas in member CL corroborates Faith's hypothesis (Deacon 1984).

These paleoenvironmental signals overlap with a period of major change in the organization of lithic miniaturization and occupation intensity at Boomplaas. During the cooler, more humid, and productive LGM climates, lithic miniaturization emphasized lower bipolar core frequencies, greater core masses, more retouched tool production, and greater frequencies of minimally-worked nodules. These patterns occurred in contexts of relatively low occupation intensity with Boomplaas being one of the few sites in the region with occupation horizons dating ~30 – 18 kcal BP. At these times, Boomplaas was not a focal point for human activity. Humans amplified and reorganized technological strategies as they occupied the site more intensively in member CL. Concurrent ratcheting of occupation signals at several southern Cape sites links the site's occupation with wider demographic changes across the southern Cape (H. J. Deacon 1976; J. Deacon 1978, 1984; Mackay 2016b; Opperman 1978; Porraz et al. 2016; Schweitzer and Wilson 1982).

With such widescale changes in geography, ecology, and population demography one would also expect to find evidence for shifts in social relations amongst hunter-gatherer groups (cf. Whitehead 2007). Anthropologists predict that increased information exchange and interaction between groups living in diverse and rapidly evolving landscapes helps buffer the effects of environmental change and scarce or unpredictable resources (Ambrose and Lorenz 1990; Wiessner 1982). Worked and decorated ostrich eggshell fragments and beads, widely argued to be tokens of social relations and exchange networks (cf. Mitchell 1996; Parkington et al. 2005), appear for the first time in Boomplaas' member CL rising threefold between sub-member CL 3 (~17 – 15 kcal BP) and CL 1 (~12 kcal BP) (H. J. Deacon 1983). Archaeologists report similarly aged geometrically engraved ostrich eggshell fragments and marine shell at Klipfonteinrand (~350 km from Boomplaas), Byneskranskop 1 (~280 km from Boomplaas), and Nelson Bay Cave (~130 km from Boomplaas), signaling the possible growth of region-wide social networks in the face of rising sea-levels and rapid climate change (Bluff 2017; J. Deacon 1984). These patterns conform to expectations from cultural evolution and ethnographic research that show cultural conformity and social network formation can have substantial fitness benefits especially in contexts where environments are spatially variable (i.e. Boyd & Richerson 1988).

5 Conclusion

We show that the structure and organization of lithic miniaturization processes involving high core reduction intensity coupled with increased bipolar and bladelet core frequencies and unretouched tool use strongly related to precipitation seasonality. Drawing on the broader Boomplaas archive we show that during the Late Glacial, humans converged on a small number of high payoff strategies drawing on increased technological efficiency. This is associated with greater production of ostrich eggshell ornaments and water containers, and a reorganized subsistence strategy geared towards greater exploitation of low-ranked prey. Concurrent ratcheting of occupation signals at several southern Cape sites links the Boomplaas occupation with wider coupled environment-demographic changes and sea level rise across the southern Cape at this time. Our data show that global climatic events such as the LGM manifest in different ways in different regions. Not all manifestations were universally harsh, or risky, and not all resulted in the same lithic technological responses. Considered as a suite of predictors, aridity, climatic unpredictability, and reduced bio-productivity, on the other hand, appear to link lithic technologies with adaptive strategies in several regions including Australia, Southern Africa, and South Asia.

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8 FIGURE CAPTIONS

Figure 1: Map showing the location of Boomplaas Cave and other sites mentioned in the text. Green dots mark paleoenvironmental sources, white dots mark archaeological sites. Dotted line marks the extent of glacial coastline -120m from the current shoreline. BPA: Boomplaas, CC: Cango Caves; SWP: Seweweekspoort; NBC: Nelson Bay Cave; KAN: Kangkara; BNK 1: Byneskranskop 1; KFR: Klipfonteinrand.

Figure 2: Quartz flakes from Boomplaas' LGM and Late Glacial members.

Figure 3: Quartz cores from Boomplaas' LGM and Late Glacial members. A: Quartz radial core; B: Quartz anvil-assisted freehand bladelet core; C & D: crystal quartz bipolar bladelet cores.

Figure 4: Comparison of LGM and Late Glacial lithic variables, anthropogenic input into the faunal assemblage, and the microfauna seasonality index.